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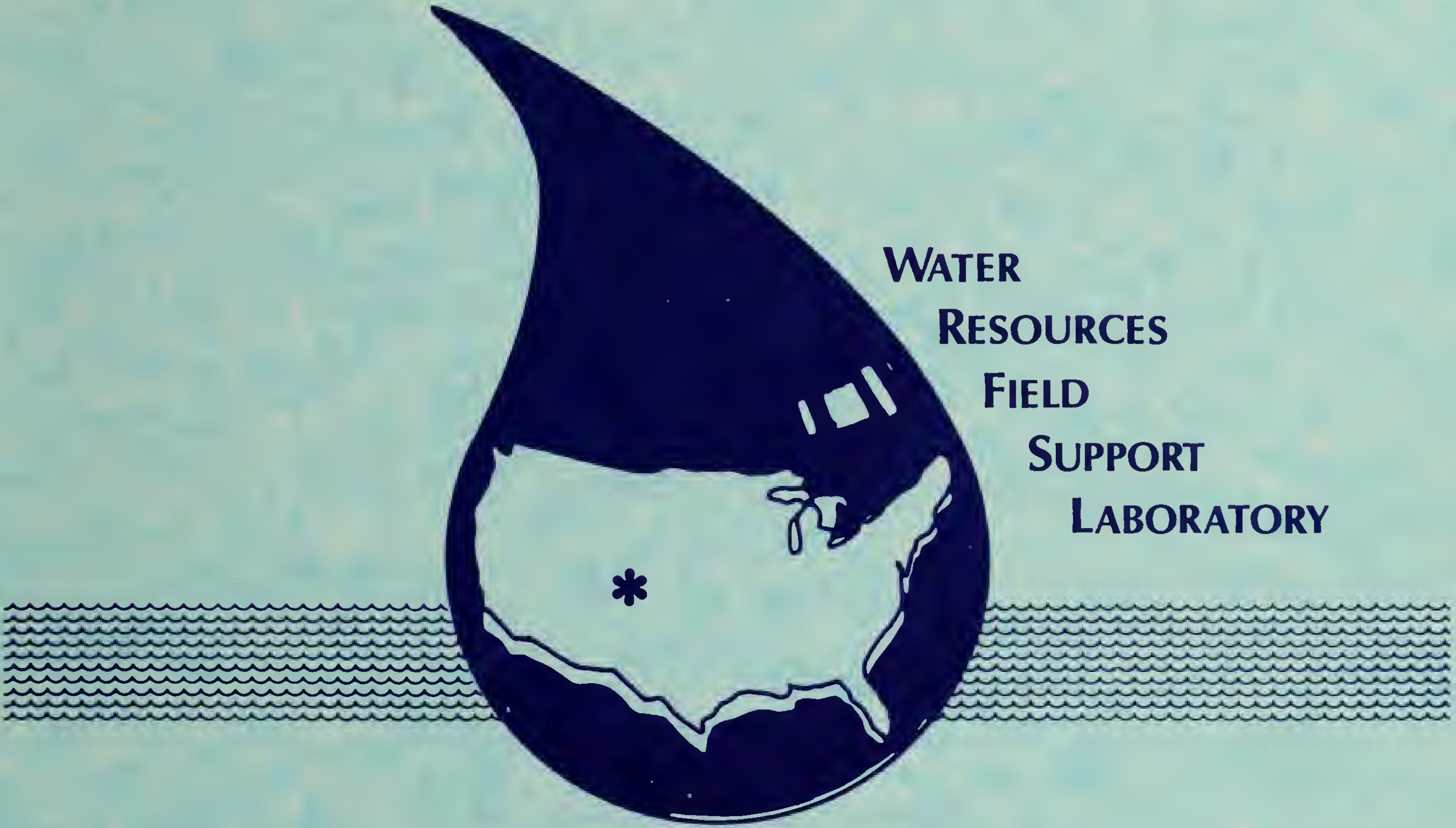
JUNE — AUGUST 1983



WRFSL Project Report No. 84-ROMO-1

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Submitted to:

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Fort Collins, Colorado 80523

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April 1984

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TABLE OF CONTENTS

INTRODUCTION 1

FIELD SITE AND DATA COLLECTION 1

SEDIMENT TRANSPORT AND HYDRAULIC GEOMETRY RELATIONS 2

Bedload Transport 3

Hydraulic Geometry 4

Temporal Variability 5

CONCLUSIONS 6

ACKNOWLEDGMENTS 6

REFERENCES 8

LIST OF FIGURES

Figure 1. Horseshoe Park Study Area 10

Figure 2. Bedload transport rate (i_b) as a function of stream power (ω) and median grain size (D_{50}); $\log(i_b) = -2.76+1.16\log(w)+0.72(D_{50})$ 11

Figure 3. At-a-station hydraulic geometry relationship between discharge and velocity 12

Figure 4. At-a-station hydraulic geometry relationship between discharge and depth 12

Figure 5. Comparison between water discharge and bedload transport rate, June-August, 1983 13

Figure 6. Cross section upstream of sediment sampling site depicting aggradation in early June and subsequent degradation in late June and July 14

LIST OF TABLES

Table 1. Discharge and sediment sample data for Fall River, 1983 9

INTRODUCTION

In many streams and rivers, the proportion of material transported as bedload is a relatively small percentage (<20%) of the total sediment load. However, as the bed and banks of a "self-formed" alluvial channel are composed largely of this material, its potential for movement ultimately controls the stability of the river. Further interest in bedload transport phenomena has been sparked by a number of recent studies which demonstrate high spatial and temporal variability in transport rates.

Although interest in the topic is high, complete sets of bedload sample data are relatively scarce. The purpose of this report is to present the results of sediment discharge measurements made at Fall River, Rocky Mountain National Park during the 1983 summer field season.

FIELD SITE AND DATA COLLECTION

The Lawn Lake flood of July 15, 1982 resulted in impressive channel changes along Roaring River and Fall River, Rocky Mountain National Park (Figure 1). Flood waters incised deep gulleys into the glacial deposits which mantle the Roaring River valley. Much of this eroded material was then deposited as a coarse debris fan in the broad low-gradient valley of Fall River in the area known as "Horseshoe Park." The disturbed portions of these streams provide abundant sediment sources for downstream reaches and the sediment load of Fall River has been greatly increased.

As part of field studies begun in May, 1983, a sediment sampling station was established on Fall River approximately 400 meters downstream of the alluvial fan terminus. At the cross section selected, the stream is relatively straight, has near vertical banks, uniform bed topography and maintains a single channel.

Twenty-one bedload samples were collected between early June and mid-August using a Helley-Smith bedload sampler (Helley and Smith, 1971). Measurements were taken every 0.5 meter across the channel giving 18 measurement stations. At each station, the sampler was lowered to the bed for a fixed time period, usually 30 seconds. The collected sediment was emptied into a bucket when the sampler was approximately two-thirds full. Thus the total sample actually represents an average transport rate across the section. Split portions of the samples were sieved by the U.S. Bureau of Reclamation, Denver, Colorado. A cumulative frequency curve for each sediment sample was constructed from the sieve data. Discharge measurements were made using a Price current meter and wading rod. Flows ranged from less than 1.0 m^3/sec to over 10.0 m^3/sec during the spring snowmelt period. The duration and peak of runoff in 1983 was far greater than the long term average.

Hydraulic data obtained during sediment sampling or stream gaging included: discharge, width, depth, velocity and water surface slope. From these data, values of cross-sectional area, unit stream power and Froude Number were calculated. Unit bedload transport rate was calculated from the total weight of the sample collected. Characteristics of the sediment mixture such as median grain size (D_{50}) and sediment sorting (σ) were determined graphically from the cumulative frequency curve for each sample (Folk, 1966). The data used in the following analyses are presented in Table 1.

SEDIMENT TRANSPORT AND HYDRAULIC GEOMETRY RELATIONS

Sediment characteristics are inextricably tied to the hydraulic properties of the flow in problems of sediment transport. The physical properties of the sediment determine the type and quantity of material to be transported. The hydraulic properties of the channel and the flow define the transport capacity of the stream. Simons and Richardson (1966) suggest that in the simplest sense bedload transport rate (i_b) can be represented by:

$$i_b = f(\gamma_s, \gamma_f, T, \nu, D_{50}, \sigma, w, d, v, S) \qquad (1)$$

where γ_s and γ_f are the specific weights of the solid and fluid respectively, T is the water temperature, ν is the kinematic viscosity of water, D_{50} is a characteristic sediment size, σ is the sediment sorting, w is the stream width, d is the average flow depth, v is the average velocity, and S is the water surface slope. Many of these variables are not independent and their interactions are complex.

Bedload Transport

Sediment load is commonly related to discharge by means of "sediment rating curves." Although such curves offer a simple predictive relationship, sediment transport is not controlled by discharge. Bagnold (1966) first introduced the concept of stream power per unit bed area as the theoretically correct indicator of the transport ability of the stream. Unit stream power (ω) as defined by Bagnold is:

$$\omega = \frac{\rho g Q S}{w} = \gamma_f \, dSv \qquad (2)$$

where ρ is the density of water, g is the gravitational acceleration and γ_f, S, d, v, and w are as defined above. Field studies by Leopold and Emmett (1976) have verified the utility of this approach.

A stepwise linear regression procedure was used to develop a multivariate equation to express bedload transport rate as a function of a number of independent variables. In the stepwise procedure, variables are added to the regression sequentially. At each step, the regression is re-examined for the appropriateness of the multivariate model. Variables with non-significant partial F values are removed and the model is refitted using the remaining variables. Unit stream power (ω), Froude number (Fr), median grain size (D_{50}) and sorting (σ) were used as independent variables. The resulting regression equation is:

$$\log(i_b) = -2.76 + 1.16\log(\omega) + 0.72(D_{50}) \qquad (3)$$

where i_b is in Kg/M/sec, ω is in N/M/sec, and D_{50} is in millimeters. This equation has a coefficient of determination of 0.67, and is represented graphically in Figure 2. Bedload transport rate is thus positively correlated with stream power and sediment size. The positive correlation between transport rate and unit stream power is as expected but the positive correlation between grain size and transport rate is surprising. Bedload transport rate often decreases with increasing grain size at a given stream power. The observed relationship suggests that the threshold for particle motion was exceeded for most of the samples taken.

Hydraulic Geometry

The hydraulic geometry of river channels has become a standard descriptive tool since Leopold and Maddock (1953) first introduced the basic relations. They demonstrated that changes in the width, depth and velocity of flow change as power functions of discharge:

$$w = aQ^b \qquad d = cQ^f \qquad v = kQ^m \qquad (4)$$

When width, depth and velocity are plotted against discharge on log-log paper the data often plot as a straight line. However, Richards (1982) suggests there is no theoretical basis for the power function relationships and there may be significant departures from the straight line model where changes in channel roughness occur as discharge is increased.

The at-a-station hydraulic geometry relations for the Fall River data are shown in Figures 3 and 4. The width-discharge relation is not included as there is no significant change in width with change in stage. This is a reflection of the vertical banks of the cross section.

There is a noticeable non-linear trend in both plots (i.e., Figures 3 and 4) and the data are best fit by second order polynomials rather than straight lines. The hydraulic geometry relationships for Fall River are:

$$\log(v) = -0.60 + 1.11(\log Q) - 0.45(\log Q)^2 \quad (5)$$

and

$$\log(d) = -0.37 + 0.10(\log Q) + 0.40(\log Q)^2 \quad (6)$$

These non-linear trends are a reflecton of the influence of bedforms on hydraulic conditions. In a sand bedded stream the bed is successively formed into ripples, dunes, plane bed, and antidunes as stream power is increased (Simons and Richardson, 1966). The development of bedforms gives rise to a particular type of flow resistance known as "form roughness." Dunes offer the greatest resistance in subcritical ($Fr < 1.0$) flows of the type observed at the sample site.

Temporal Variability

Sediment transport in mountain streams is often discontinuous reflecting variability in sediment supply from upstream source areas (Hayward, 1979). The trend in Fall River bedload transport rates over the summer months is shown in Figure 5. In general, bedload transport rates at the sample site follow the trend of the snowmelt hydrograph. However several departures are apparent. Bedload transport rates are low in the early part of June even though discharges are moderately high. In early July, several cases of high transport rates for moderate discharges are noted.

Surveyed channel cross sections upstream of the measuring station show episodic scour and fill (Figure 6). Low bedload transport rates correspond with periods of channel aggradation as the upstream reaches are being used as sediment stores. Subsequent degradation in these reaches results in high measured transport rates at the sampling station. Thus the variability in bedload transport rates is a function of non-uniform sediment supply from upstream reaches rather than changes in stage.

CONCLUSIONS

The analyses of bedload discharge data from Fall River, Rocky Mountain National Park can be summarized as follows:

(1) Stream power per unit bed area and median grain size are good predictors of unit bedload transport rate as indicated by the good correlation (R^2 = .67) of a multiple linear regression.

(2) The presence of bedforms strongly affects the hydraulic geometry relationships at the sampling station.

(3) Periods of low bedload transport rates at the sampling station correspond to episodes of channel infilling in upstream reaches while high transport rates correspond to episodes of scour.

ACKNOWLEDGMENTS

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REFERENCES

Bagnold, R. A., 1966. An approach to the sediment transport problem from general physics, U.S. Geological Survey Professional Paper, 422-I.

Folk, R. L., 1966. A review of grain-size parameters, Sedimentology, Vol. 6, pp. 73-93.

Hayward, J. A., 1979. Mountain stream sediments, in Physical Hydrology-New Zealand Experience, edited by D. L. Murray and P. Ackroyd, New Zealand Hydrological Society, Wellington, pp. 193-212.

Helley, E. J. and Smith, W., 1971. Development and calibration of the pressure difference bedload sampler, U.S. Geological Survey Open File Report, 17 p.

Leopold, L. B. and Emmett, W. W., 1976. Bedload measurements, East Fork River, Wyoming, Proceedings of the National Academy of Sciences, U.S.A., 73, 1000-1004.

Leopold, L. B. and Maddock, T. M., 1953. The hydraulic geometry of stream channels and some physiographic implications, U.S. Geological Survey Professional Paper, 252.

Richards, K., 1982. Rivers, form and process in alluvial channels. Methuen & Co., New York, 358 p.

Simons, D. B. and Richardson, E. V., 1966. Resistance to flow in alluvial channels, U.S. Geological Survey Professional Paper, 422-J.

Table 1. Discharge and sediment sample data for Fall River, 1983

Date	Time	Discharge (m^3/s)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)	Average Velocity (m/s)	Unit Stream Power (Kg/m/sec)	Unit Bedload Transport Rate (Kg/m-s)	Median Grain Size (mm)
6-9	1130	3.51	4.34	9.0	0.48	0.81	1.24	0.07	0.70
6-10	1100	4.30	4.90	9.1	0.54	0.88	1.52	0.09	0.78
6-10	1915	6.37	5.93	9.6	0.62	1.07	2.12	0.07	0.66
6-11	1800	6.80	6.00	9.5	0.63	1.13	2.28	0.08	0.42
6-13	1900	2.83	4.51	9.2	0.49	0.63	0.99	0.14	0.52
6-14	930	2.26	4.20	9.3	0.45	0.54	0.78	0.20	0.64
6-16	1050	2.83	4.46	9.3	0.48	0.63	0.97	0.16	0.72
6-17	1715	5.66	5.02	9.5	0.53	1.13	1.91	0.42	0.96
6-20	1800	7.14	7.33	9.5	0.77	0.97	2.39	0.41	0.92
6-23	1030	8.27	7.59	9.5	0.80	1.09	2.79	0.37	0.84
6-23	2400	10.76	8.31	9.6	0.87	1.29	3.59	0.61	1.00
6-24	2400	10.48	8.23	9.5	0.87	1.27	3.53	0.99	1.25
6-27	1500	6.85	6.71	9.5	0.71	1.02	2.31	0.76	1.20
6-29	1030	7.36	6.65	9.5	0.70	1.10	2.46	0.55	1.20
7-1	1145	7.08	6.25	9.5	0.66	1.13	2.38	0.85	1.50
7-8	1200	8.21	7.40	9.5	0.78	1.11	2.77	0.30	0.94
7-11	2115	7.79	6.99	9.4	0.74	1.11	2.63	0.48	1.00
7-15	1430	4.22	4.83	8.9	0.54	0.87	1.50	0.41	1.40
7-20	1140	4.30	4.96	9.0	0.55	0.87	1.53	0.34	1.40
7-27	1345	3.09	4.44	9.1	0.49	0.70	1.10	0.09	1.17
8-12	1330	1.95	3.80	9.0	0.42	0.51	0.69	0.01	0.84

NOTE: Water surface slope maintained a nearly constant value of .0032 for all samples.

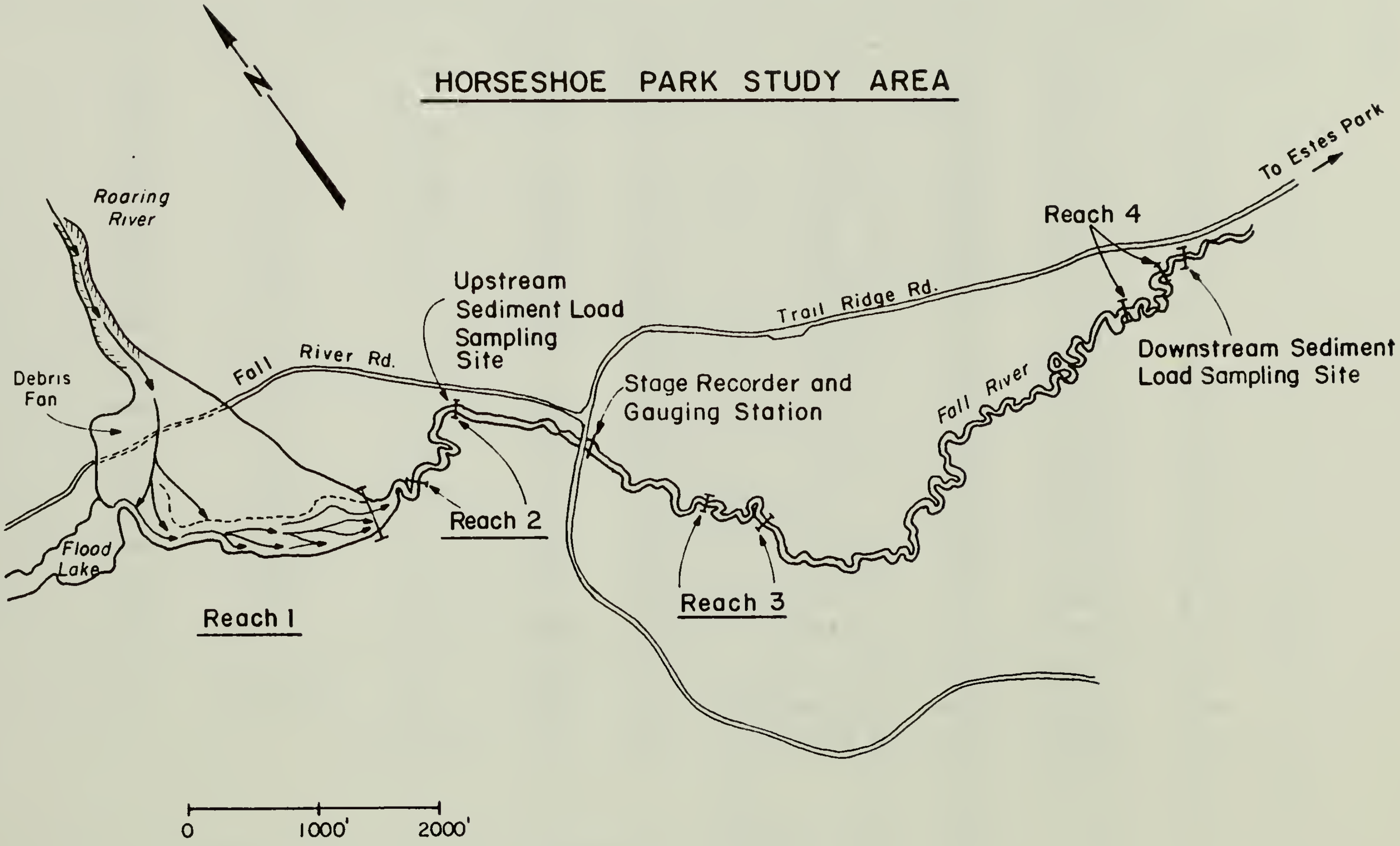
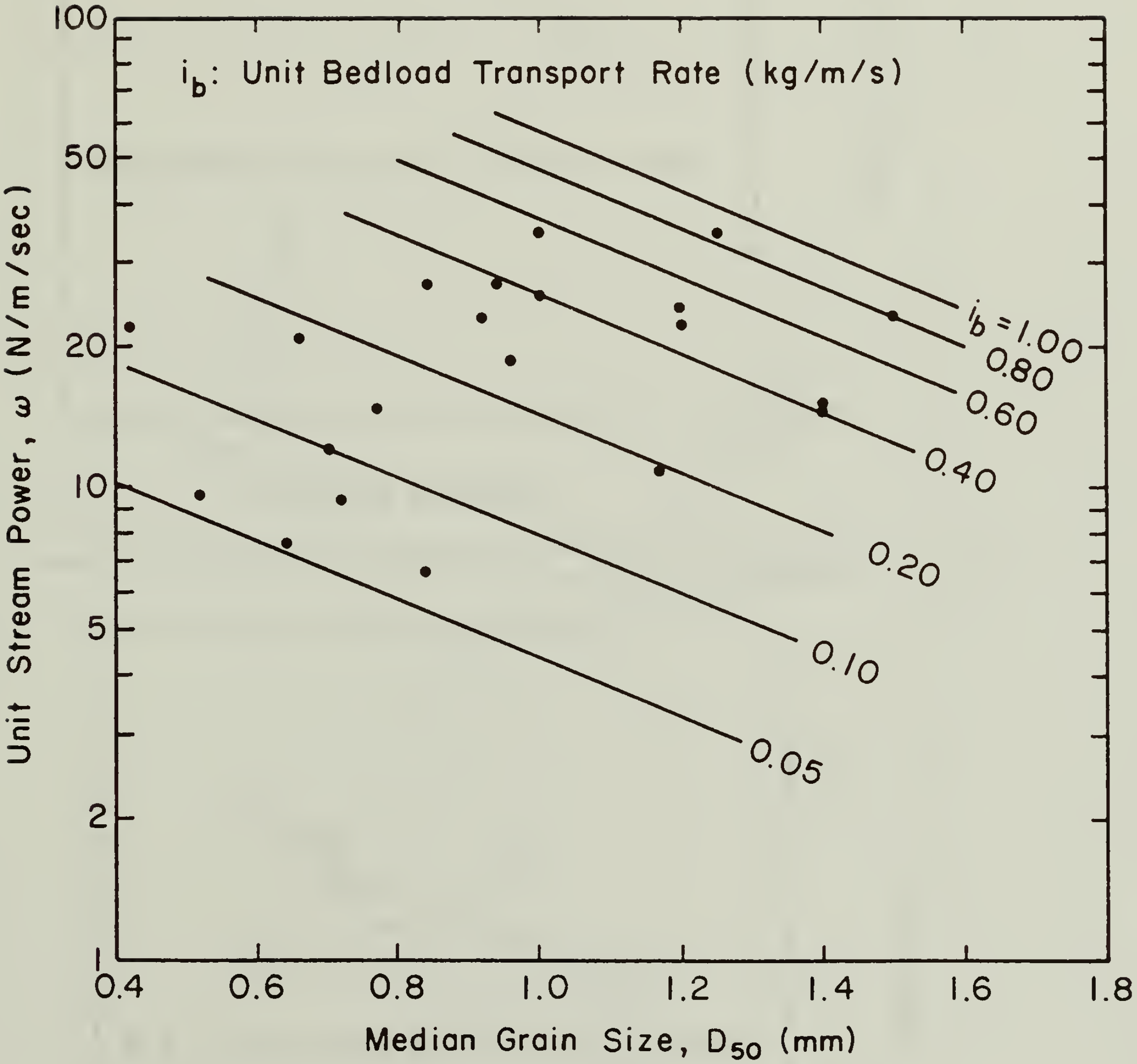

HORSESHOE PARK STUDY AREA
N
To Estes Park
Roaring River
Debris Fan
Flood Lake
Reach I
Fall River Rd.
Upstream Sediment Load Sampling Site
Reach 2
Stage Recorder and Gauging Station
Trail Ridge Rd.
Reach 3
Fall River
Reach 4
Downstream Sediment Load Sampling Site
0
1000'
2000'

Figure 1. Horseshoe Park Study Area.



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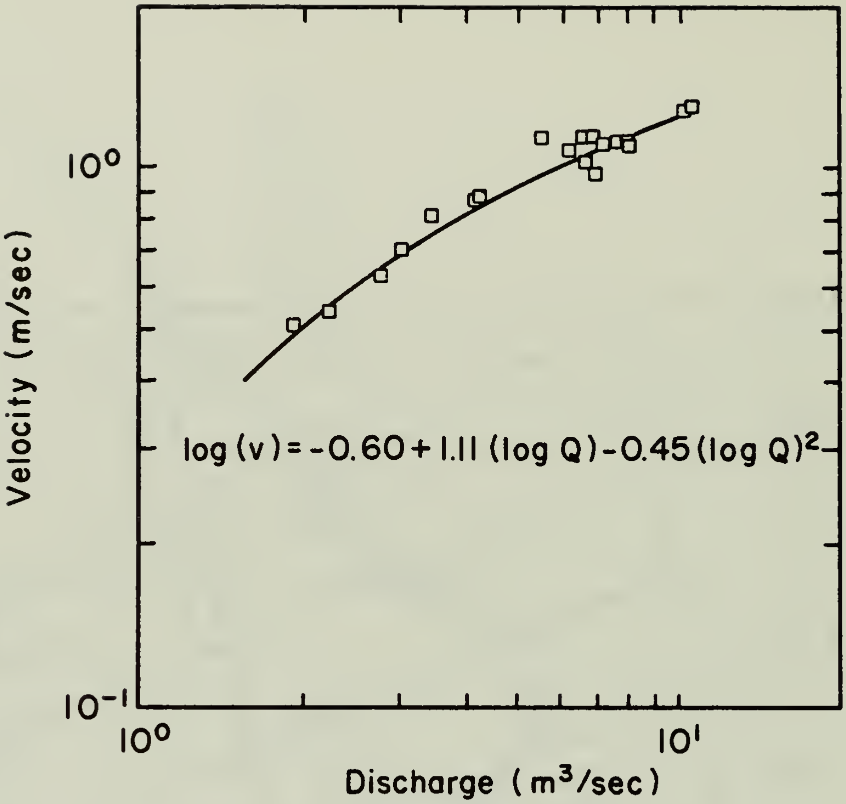

Figure 3. At-a-station hydraulic geometry relationship between discharge and velocity.

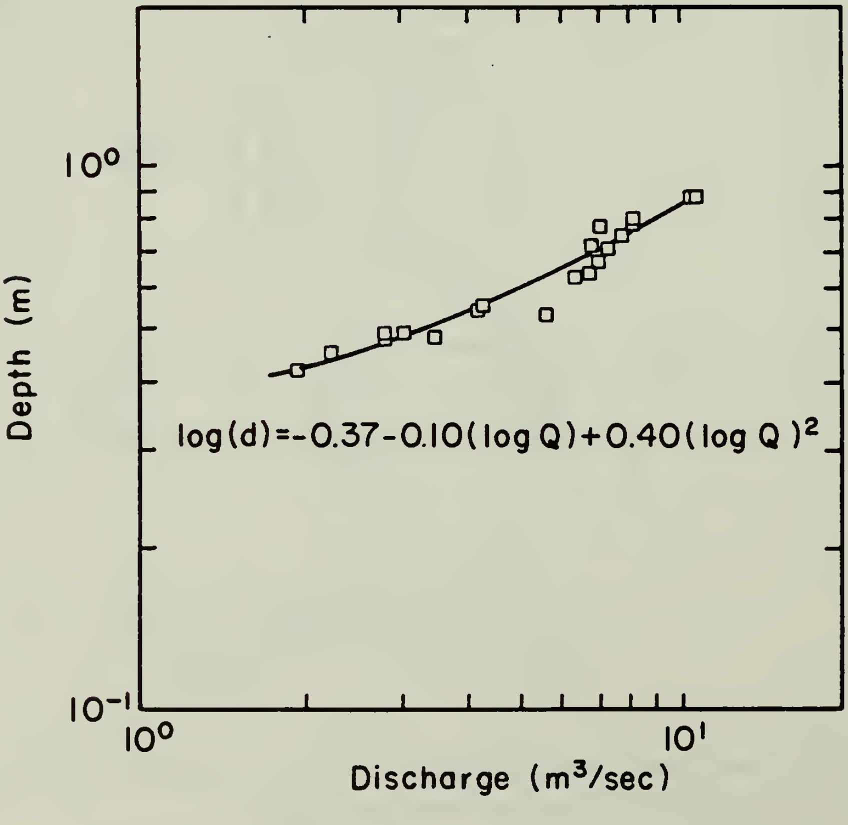

Figure 4. At-a-station hydraulic geometry relationship between discharge and depth.

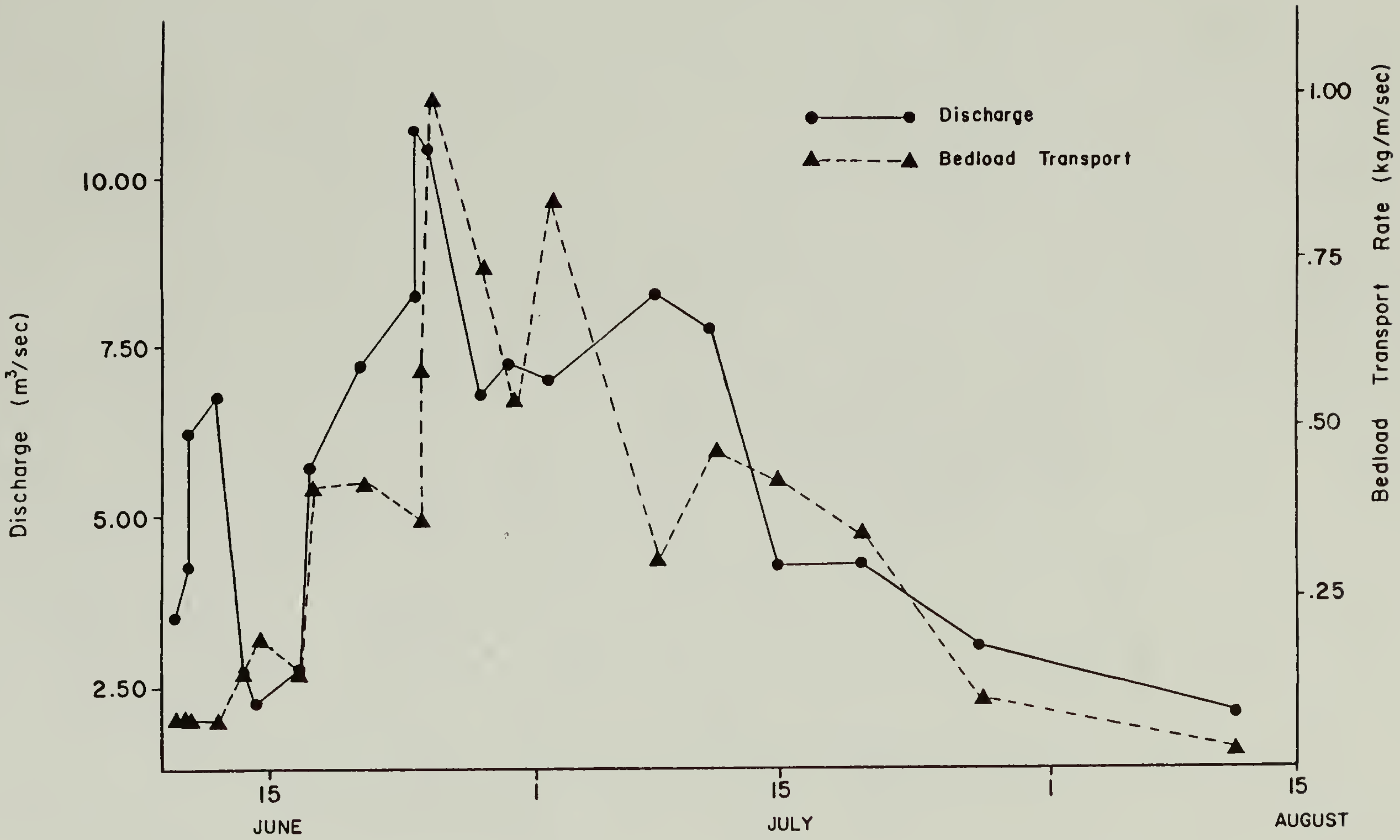

Figure 5. Comparison between water discharge and bedload transport rate, June-August, 1983.

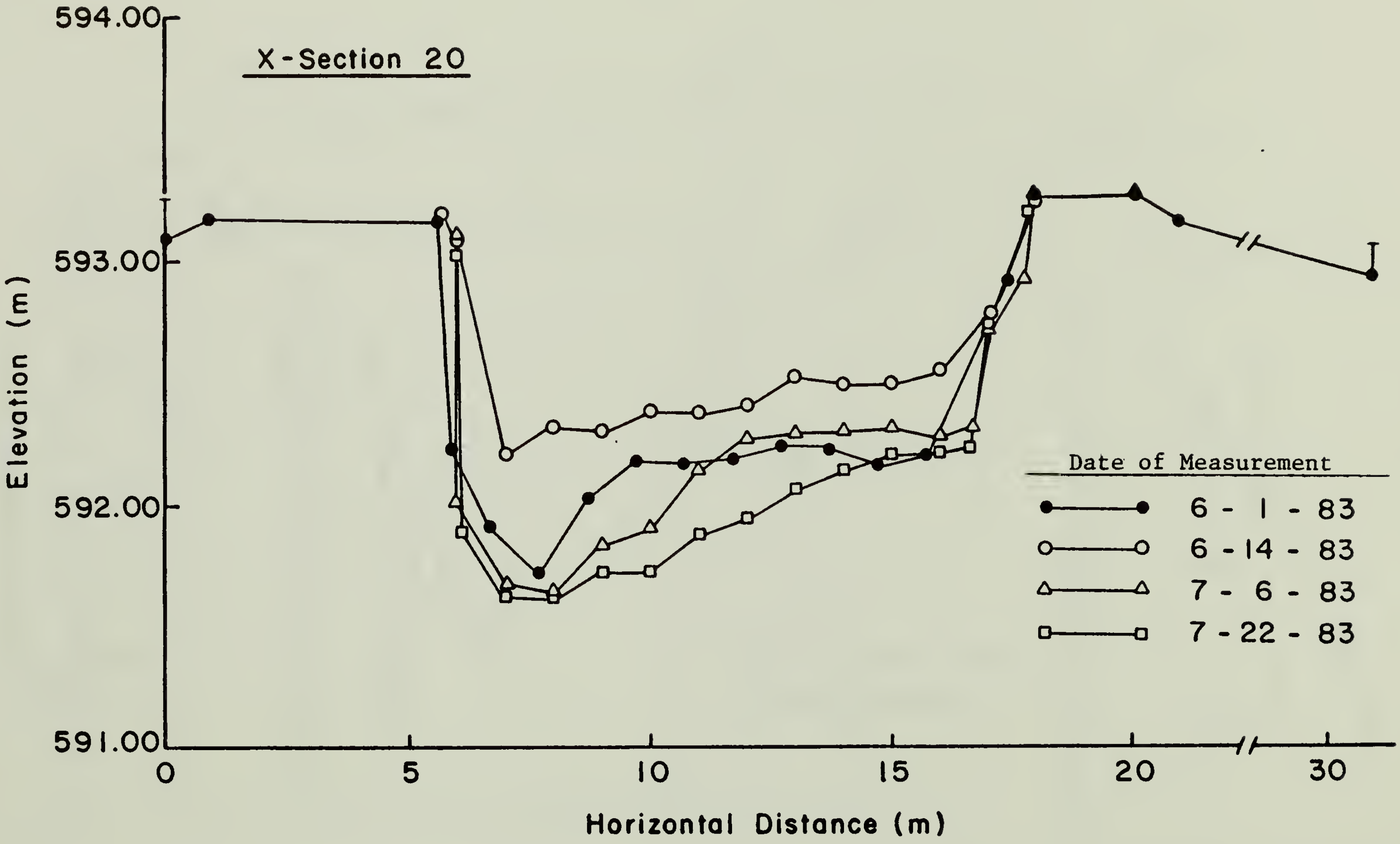

Figure 6. Cross section upstream of sediment sampling site depicting aggradation in early June and subsequent degradation in late June and July.

March 3, 1849

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